Design and Development of an On-line Cerenkov Photon Counting Based Heavy Water Leak Detection System Suitable for Indian Pressurised Heavy Water Reactor Systems

Synopsis of the Thesis to be Submitted to the Mangalore University for the Award of the Degree of Doctor of Philosophy in Physics

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1.0 Introduction

In Pressurized Heavy Water Reactor (PHWR) natural uranium is fuel and D_2O is used as primary coolant and moderator (Bajaj and Gore, 2006). The D_2O flows inside the pressure tubes (PT) containing fuel bundles. Primary Heat Transport (PHT) system transports heat generated in the reactor core to steam generators (SG), where light water boils-off in secondary side to generate steam for the turbine (Revankar and Jovica, 2009). SGs are shell and tube heat exchangers where heavy water flow through thin metallic tubes of 1 mm thickness. The possibilities of SGs leaking can not be ruled out completely due to the impact of foreign material such as construction debris, or due to maintenance activities (Rao, 2014). Shell and tube type heat exchangers are used in PHWRs to cool the equipment and process systems of PHT and moderator systems. Failure of SG or HX tubes will contaminate the secondary coolant water flowing in the shell side of SG/HX with fission and activation products present in the primary side. Important activation products in PHWR is tritium (^3H), produced by neutron activation of primary coolant and moderator water. Fission products enter the primary coolant due to release from failed fuel elements and neutron-induced fission of the uranium debris present in the core components (Lewis, 2017; Gopalakrishnan et al., 1995). A leak in SG or HX tube will contaminate the secondary coolant with ^3H and fission products. ^3H contamination is one of the major concerns because these radionuclides may enter the public domain and deliver radiation dose to the public. Loss of D_2O is also not acceptable due to the economic point of view of reactor operation.

Hence for prompt detection of D_2O leak from PHT and moderator system online D_2O to H_2O leak detection systems (^3H-in-water monitor) are installed in Indian PHWRs (AERB/D-15, 2015). However, there are difficulties in detecting radioactive contamination with the ^3H-in-water monitors because the low energy beta emitted by ^3H are too weak to detect by in situ detectors (Wook et al., 2013). The efficiency of the plastic sponge scintillator detector used for ^3H detection deteriorates due to the pick up of impurities from the water flowing through it as well as due to turbidity present in the secondary coolant. Therefore frequent replacement of detector is required to operate the system (Singh and Rathnakaran, 1987). ^{16}N and ^{19}O are other two activation products observed in the primary coolant and moderator (AERB/D-12, 2015). These gamma radiation emitters are used as tracers for D_2O leak detection in PHWRs, in addition to a ^3H detector, using NaI(Tl) detectors. The ^{16}N and ^{19}O are short-lived isotopes ($T_{½}$ = 7.3 s and 26 s), and hence the detectors are to be kept very close to the SG to find the leak. Due to higher radiation levels in the area inside the reactor building, only very high leak rates can be detected by this system (Mitra, 2005). During non-availability of these systems, leak detection is carried out by the off-line method in which periodic manual sampling and analysis for tritium activity level in H_2O are performed in the laboratory. This monitoring program requires skilled laboratory personnel and analytical capabilities.

Lack of instantaneous results may delay the remedial action program during the operation of the power plants. As D_2O leak progresses, the background activity of ^3H in secondary coolant builds up due to its long half-life ($T_{½}$) of 12.3 years and hence identification of leaky one becomes difficult. Therefore the identification of leaky SG/HX is carried out by measurement of the short-lived isotope of iodine (^{134}I $T_{½}$ = 52 min) by trapping the fission products entering into secondary coolant subsequent to leak in an ion-exchange column and analysis of the resin samples by gamma spectrometry in the laboratory (Sahoo and Jain, 2003). But the method cannot be used for in-situ leak detection. For these reasons development of

reliable and rapid in situ screening technique for SG/HX leak to be given paramount importance.

Operational experience indicates that an ideal D_2O leak detection shall be (i) low background and high-efficiency system for better sensitivity, (ii) shall detect only short-lived isotopes to discriminate against the background activity buildup in the secondary coolant due to long-lived isotopes, (iii) turbidity of secondary coolant shall not deteriorate detector efficiency, and (iv) no chemicals are used for detection (Dileep et al., 2020). A technique which fulfils these requirements is a preferred choice for detection D_2O leak.

Some of the fission products and activation products observed in the primary coolant are hard beta emitters, and they produce light in water. Emission of light by beta radiation in water is called Cerenkov radiation (Cerenkov, 1937). The Cerenkov radiation can be detected by photomultiplier tubes and the activity can be quantified. The minimum electron energy, called the Cerenkov threshold energy, necessary for the production of Cerenkov radiation in the aqueous medium is ~263 keV (Ross, 1969). Hence low energy beta and gamma radiations are not detected by Cerenkov counter, and background count rate of a Cerenkov counter is very low. A use of a liquid scintillation analyzer for Cerenkov counting has been reported previously, and counting efficiency was reported to be 39±2 % for aqueous solutions taken in 20 mL glass vials without scintillator and counted in a Perkin Elmer 3170 TR/SL liquid scintillation counter (Gunther et al., 2009). Low background, high efficiency and a large volume of sample yield better sensitivity. Turbidity of the sample will not affect the performance of the Cerenkov counter (Annunziata, 1998). Short-lived isotopes such as ^{16}N and ^{19}O achieve equilibrium concentration quickly (within a few minutes) in primary coolant after the reactor starts to operate and these isotopes are prolific producers of Cerenkov radiation. Hence, this method can be used for quick detection of D_2O leak from the early stages of reactor operation. Flow scintillation analysis is an application of liquid scintillation counting technique

for the quantitative analysis of radioactivity in a flowing system (Annunziata, 1998). Since water itself is a scintillating medium in Cerenkov photon emission, implementation of online monitoring of activity is relatively simple (Robert et al., 2005). These observations indicated that an online Cerenkov counter could be designed and developed for D_2O leak detection, which will offset most of the deficiencies observed in the existing methods. The isotopes which are prolific produces of Cerenkov radiation observed in the primary coolant include ^{134}I, ^{138}Cs, and ^{19}O.

It is clear from the above discussion that the unique features of Cerenkov photon counting technique (low background high-efficiency technique, discrimination against long-lived isotopes, no chemical requirement for activity determination and simple design of a situ system) can be exploited to construct an on-line heavy water leak monitoring system suitable for PHWRs for early detection and identification of leaky component. Hence, a study was undertaken to design and develop a system for heavy water leak detection. The details of the newly designed system and the successful demonstration of its application are discussed in the thesis.

2.0 Importance of the study

The techniques used for heavy water leak detection in SG/HX of PHWR require improvement since the method is offline one. On-line leak detection will save precious heavy water and reduce generation of radioactive liquid waste. Operational experience indicates that a heavy water leak detector shall be (i) low background and high-efficiency system for better sensitivity, (ii) shall detect only short-lived isotopes to discriminate against the background activity buildup in the secondary coolant due to long lived isotopes, (iii) no chemicals are used for detection (iv) an in situ system. The features of Cerenkov photon counting system cater the above requirements and hence detailed study would yield a new technique to develop an online

heavy water leak detection system which would be able to detect leak and identify leaky component promptly.

3.0 Aim and objectives of the study

The aims and objectives of the study are:

i. To study the suitability of Cerenkov photon counting technique for detection of heavy water leak from primary coolant to secondary coolant in PHWRs, and

ii. Development of an on-line heavy water leak monitoring system based on Cerenkov photon counting technique for PHWRs.

4.0 Overview of the work done

The study included characterization of radioisotopes in primary coolant, identification of radionuclides in the primary coolant which produce the Cerenkov in aqueous medium and estimation of their concentration, Cerenkov counting of primary coolant samples and diluted primary coolant samples, Cerenkov counting of secondary coolant from HX outlet during a heavy water leak incident to identify the leaky HX, comparison of the data with ^{3}H activity in the secondary coolant for leak identification, design requirements of an on-line leak detection system for identification of leaky SG/HX, development of new online system for leak detection and identification using Cerenkov radiator and field test during heavy water leak incident in SG.

4.1 Characterization of radioisotopes in the primary coolant

D_2O sample was collected from the primary coolant sampling station while the reactor was under steady-state operating condition. Isotopic analysis of primary coolant sample was done by counting 5 mL of sample in a plastic vial on HPGe detector, mentioned in the previous section, which was calibrated for the same geometry. Decay correction for the delay in sample

collection and analysis is incorporated by option available in Inter Winner software. Observed iodine activity was analyzed to find the source of the fission products, from defective fuel element and/or fine fuel debris deposited on in-core surfaces (uranium contamination) (IAEA NF-T-2.1, 2010). The concentration of short lived fission products which are prolific producers of Cerenkov radiation in primary coolant was estimated from the uranium contamination level. Concentrations of activation products in the primary coolant, which are high energy beta emitters and produce Cerenkov radiation were also estimated.

4.2 Cerenkov counting of primary coolant samples

Cerenkov counting method is one of the liquid scintillation counting methods. PerkinElmer make liquid scintillation analyzer 2900TR was used for Cerenkov photon counting in laboratory studies. Cerenkov counting was performed with 20 mL volume glass and polythene plastic vials. Experiments were carried out for various volumes of ^{90}Sr-^{90}Y liquid standard in the vial to study the volume effect. Experiments were carried out to identify the radionuclides in the primary coolant, which contribute to Cerenkov radiation in the aqueous medium. The primary coolant water sample was diluted by10^2,10^3, 10^5 and 10^6 times and 20mL of the aliquot of each diluted sample was subjected to Cerenkov counting and results were noted to study the feasibility of the method for leak detection.

4.3 D_2O leak detection by ^3H counting

Secondary coolant samples were collected for leak detection from various HXs/SGs. Tritium activity in samples was measured by dispensing 1mL of the sample in a counting vial containing 5 mL liquid scintillation cocktail and counted in Liquid Scintillation Analyser (Annuziata, 1998). Observed ^{3}H activity in secondary coolant from various HX outlet was noted. Increase in tritium concentration in H_2O indicates D_2O to H_2O leak from HX. But tritium

activity was comparable in more than one HX samples, and hence it was difficult to identify the HX, which has developed a leak.

4.4 D_2O leak detection and identification of leaky HX by Cerenkov counting technique

Secondary coolant from HX out let was taken in 20 mL plastic vials without scintillator and counted on Liquid Scintillation Analyzer. D_2O leak was detected by comparing the Cerenkov photon count rate with that of the blank. A discrimination ratio significantly higher (30%) than the average count rate for all heat exchangers was used to identify the leaky one (Mc Donald et al., 1990).

4.5 Design and development of online Cerenkov photon counting system for D_2O leak detection and identification of leaky HX/SG

Based on the observations and experience gained from laboratory experiments, an online HX/SG leak monitoring system based on Cerenkov photon counting technique was designed and constructed. Field test of the system was carried out during heavy water leak in SG in PHWR during full-power operation. The results were verified by estimating the expected count rate due to fission and activation products and comparing it with count rate observed from the newly developed system. The leak was confirmed by comparing with the results of the traditional method of leak detection. The system was put on-line for three months, and performance was monitored.

5.0 Outline of the thesis

The thesis has been divided into four chapters. The contents of these chapters are briefly outlined below.

Chapter 1. Introduction and literature survey

This chapter presents the introduction and importance of the present study. It describes the traditional method of heavy water leak detection in steam generators and heat exchangers in PHWRs and the need for an alternate method to yield better results when compared to the existing method. A review of the literature published on PHWR, heavy water leak detection systems presently available is presented in this chapter. The important requirement of an online leak monitoring system for detection and identification of leaky SG/HX during full power operation of the reactor is included. Literature published on the application of Cerenkov photon counting technique for radioactivity monitoring in primary coolants, and liquid effluents in national and international journals are discussed. Feasibility of heavy water leak detection by Cerenkov counting of secondary coolant water is also explained. Aim and objective of the proposed study are also explained in this chapter.

Chapter 2. Development of online Cerenkov photon counting system

The new leak detection system consists of two parts, (i) detector assembly, and (ii) electronic rack. The detector consists of two photomultiplier tubes (PMT) positioned at 180^0 relative to each other and optically interfaced to a polythene plastic flow-through cell (height 40 mm; diameter 25 mm) with a volume of 20 cm^3. The reflector facilitates the detection of Cerenkov photons, which otherwise would not reach the PMTs. The flow cell is shielded by 30 mm lead for background reduction. The sample enters flow cell through the bottom and leaves from the top under gravity. The electronic rack consists of low voltage and high voltage power supplies, coincidence generator, summing amplifier and a central processing unit. The photomultipliers are operated in coincidence mode in order to reduce thermal and electronic noise pulses associated with each individual tube. Scintillation in the flow cell will be detected only when a signal is detected in both PMTs within a coincidence resolving time of 20 ns.

Summing amplifier reassembles the two coincident signals into a single signal with the summed intensity. A central processing unit (CPU) accepts input from summing amplifier and display counts in counts per minute. Inflow counting, the counting time is a function of flow rate and flow cell volume. The observed sample counts are normalized by sample residence time (ratio of flow cell volume to sample flow) and count rate calculations are updated by the instrument during fixed periods which can be set by the operator. The update time is adjustable over the range of 1 to 120 s. CPU activates or deactivates relay contacts based on CPM as per user set points. It also displays “counter fail” if no signal is received within 45 sec.

Chapter 3. Materials and methods

This study involved (i) evaluation of the feasibility of using LSA for Cerenkov photon counting, (ii) Cerenkov photon counting of the primary coolant samples using LSA, (iii) estimation of FP activity concentration in D_2O sample collected from the primary coolant during reactor operation to investigate the source of these radioisotopes, and (iv) Cerenkov photon counting of the H_2O samples from HX outlets to detect D_2O leak and identify the leaky HX.

The basic instrumentation for the Cerenkov measurements and tritium activity measurements consisted of a Tri-Carb liquid scintillation analyzer (2900 series). A high purity germanium detector of coaxial type (Canberra Enuresis, EGPC 15-1.80) coupled to a PC-aided 16K MCA and InterWinner 4.1 software (Canberra Eurysis, IW.1) was used for gamma spectrometric analysis of primary coolant samples.

Uranium contamination of the rector in-core was estimated from measured radioiodines in the primary coolant. The result was used for estimation of equilibrium concentration of short lived fission products which are prolific produces of Cerenkov radiation in primary coolant.

The results of Cerenkov counting of secondary coolant samples were used for leak detection and identification of the leaky HX. The new online leak monitoring system, developed based on Cerenkov photon counting technique, was used to detect a leak in SG during reactor operation. The observed results during leak were verified by theoretically calculated activity.

The system was used for determination of ^{19}O activity in the reactor shield cooling water, and the results were used for the estimation of thermal neutron flux.

Chapter 4. Results and discussion

This chapter presents the results and comprehensive discussion on the new method of heavy water leak detection in PHWRs using online Cerenkov photon counting system. The results and discussion can be broadly classified into the following sections:

- Optimization of sample flow cell size and sample flow for online Cerenkov counter
- Cerenkov photon counting of primary coolant D_2O samples
- Determination of fission product activity in the primary coolant
- Study on sources of FPs in primary coolant D_2O
- Estimation of in-core Uranium contamination in the primary coolant
- D_2O to H_2O leak detection and identification of leaky HX by Cerenkov photon counting using Tri-Carb 2900TR LSA
- Estimation of ^{16}N and ^{19}O activity in the primary coolant
- Estimation of hard beta-emitting radionuclides concentration in the secondary coolant at the leak detector position, placed outside the reactor building, subsequent to a D2O leak.
- Design and development of new on-line heavy water leak monitoring system using Cerenkov photon counting technique

- Performance assessment of the new leak detection system.
- Detection and identification of heavy water leak in SG of PHWR at Kaiga Generating Station

Chapter 5. Summary and conclusions

In this chapter the summary and conclusions drawn from the study are presented. Some important findings and conclusions are as follows

5.1 Cerenkov photon counting with glass and plastic vials

- Counting efficiency was higher for plastic counting vials in comparison with that of glass vials and it is due to a significant fraction of Cerenkov radiation is emitted in the ultraviolet (UV) region and plastic is better for transmission of UV radiation.
- The figure of merits (E^2/B) of the LSA used for this study were 86.5, 94.2, 92.1 and 87.4 for sample volumes 5, 10, 15 and 20 mL respectively and the corresponding value for MDLs were 0.12, 0.06, 0.04 and 0.03 Bq mL^{-1}respectivey.
- Owing to low MDL value, easy to fabricate, and low cost, 20 mL plastic sample flow cell was used in the new Cerenkov counter for leak detection.

5.2 Cerenkov photon counting of primary coolant samples

- Pulse height spectrum produced by Cerenkov photons from a sample of primary coolant D_2O sample using the Packard Tri-carb-2900TR LSA was spread in the energy range 0-50 keV spread with peaking at ~ 5 keV
- The Cerenkov photon count rate of 5 mL of a typical primary coolant sample was in the range of 6.4 E+05 to 1.03E+06 cpm, and mean value was 8.3 E+05 cpm.

- Cerenkov photon count rate (cpm) obtained from with primary coolant D_2O sample exhibited a linear dependency on the concentration of ^{134}I present in it.
- Cerenkov photon count rate with diluted primary coolant for 10^5 dilutions was higher than the background counts. These results indicate the feasibility of effective utilisation of the principle of Cerenkov counting for leak detection since dilution that takes place in SG/HX during a D_2O leak are of the same order or less.

5.3 Prolific producers of Cerenkov radiation in the primary coolant

- Gamma spectrometric analysis of primary coolant samples showed significant quantities of isotopes of I, Cs Kr and Xe in primary coolant during steady-state operation of PHWR.
- Analysis of ^{134}I activity in the primary coolant indicated sources of short-lived FP in the primary coolant are essentially due to the uranium contamination of the in-core surfaces of the reactor. Uranium contamination level was calculated and was found to be 3 and 6 g in the reactor-1 and reactor-2.
- Uranium contamination in the core, particularly on pressure tube surfaces, act as a continuous long-term source of dissolved FP in the primary coolant. In case of SG/HX leak the fissions products will enter into the secondary coolant. They were gainfully used as tracers to detect and identify leak during reactor operation in this work
- Delayed counting of primary coolant sample for isotopic activity and Cerenkov photon count rate indicated that short-lived FP contribute to Cerenkov counts essentially. Cerenkov count rate reduced to half of its original value within 60 min. The delayed counting indicated that long-lived FPs, which are low energy beta emitters, contribute less to Cerenkov counts.

- The leak detection method based on the use of ^{3}H as tracer indicates that identification of leaky HX/SG is not possible due to circulating background activity problem from ^{3}H buildup in the secondary coolant. On the other hand, this study showed that there will not be a significant buildup of isotopes which produce Cerenkov radiation in the secondary coolant because Cerenkov radiation is produced by short-lived isotopes in the primary coolant. This advantage is made use of in identification of leaky SG/HX in the new method developed in this study.

5.4 Identification of leaky HX by Cerenkov counting in LSA

- Secondary coolant samples from HXs of the PHWR were collected and subjected to Cerenkov counting during a D_2O leak incident in Kaiga NPP and the count rates for all HX samples were four to six times higher than the background count rate. It indicated D_2O leak in one of the HXs. Leaky HX was identified based on the ratio of their count rate to average count rate or discrimination ratio (DR). If DR corresponding to a particular HX sample is significantly higher (about 30%) than the average Cerenkov photon count rate for all other HXs, it is an indication of D_2O leak from that HX. In the particular case studied in this work, the average count rate for all other HXs was 51 cpm, and count rate for a particular HX which was leaking was 62 cpm, DR was >30%. Thus, both D_2O leak and leaky HX were identified.
- Crucial information was obtained from the Cerenkov counting of secondary coolant samples for the development of the new system. Since manual sampling and analysis will lead to the time delay in leak detection, an online system was designed and developed for prompt detection of a leak.
- An online system will facilitate to make use of short-lived activation products such as ^{19}O as a tracer in addition to FPs.

5.5 Design and development of the online Cerenkov counter

- Based on the experimental observations obtained from the analysis of primary coolant samples by gamma spectrometry and Cerenkov counting using LSA, a D_2O leak detection system based on Cerenkov photon counting technique was designed and developed.

5.6 Performance evaluation of the online D_2O leak detection system

- Background count rate observed with the new Cerenkov counting system developed was 3.9 ± 3.5 cpm, and counting efficiency achieved with $^{90}Sr/^{90}Y$ liquid standard was 22.2%. Shor-lived activation and FP are hard beta emitters and are prolific producers of Cerenkov radiation. These isotopes are detected with efficiency similar to that obtained for $^{90}Sr/^{90}Y$ by the system. There is no interference from low energy beta radiation or gamma rays as they cannot produce Cerenkov radiation, and hence detector background is very low. A larger volume of sample can be taken for analysis in comparison to conventional liquid scintillation counting since the addition of liquid scintillator is not required. These inherent properties of the Cerenkov counter enable the system to detect low-level activities.
- MDA achieved was 5.0 E-02 Bq mL^{-1}. Such a low level of MDA was achieved due to low background, high detection efficiency and higher sample volume (20 mL) when compared to conventional liquid scintillation counting.
- Unlike conventional liquid scintillation counting technique, reduction in counting efficiency due to chemical quenching is non-existent in Cerenkov counting. The purity of the steam condensate sample was observed to be similar to that of distilled water. Therefore, colour quenching can be ignored, and the leak detector performance does not need quench correction to be applied.

- Short-lived hard beta emitters produce Cerenkov emission among the radionuclides. Hence the detector contamination due to flow of contaminated secondary coolant was not observed and hence no memory effect.

5.7 SG leak detection using the online system

- The prototype system was connected online in the PHWR reactor to test the efficacy.
- Steam condensate samples from steam generators SG1, SG2, SG3, and SG4 during a suspected SG tube leak at KGS NPP during full power operation of the reactor showed count rates of 8±4, 8±4, 18±7 and 6±4 cpm respectively. A D_2O leak event would result in the buildup of activity in the secondary coolant of all SGs due to recirculation which indicates a leak in one of the SGs. The leak from SG3 was identified through the determination of the discrimination ratio (DR); the parameter used to identify the leak. DR of the leaky SG was higher than 30% when compared to normally operating SGs.
- Radioisotopes in the primary coolant ^{19}O, ^{88}Rb, ^{134}I, and ^{138}Cs with mean β energy emission of 2.75, 1.75, 2.1, 0.62 and 1.24 MeV respectively were the isotopes which contributed to Cerenkov radiation.
- The minimum detectable D_2O leak rate of 3.6 kg h^{-1} was achieved by the system developed in this study.
- The system could successfully detect the leakage in SG and also identify the leaking SG, which is not possible using the conventional ^{3}H-based system.

5.8 Merits and demerits of the system

The online Cerenkov photon counter developed in the present study for leak detection has following advantageous over ^{3}H-in- water monitoring method, which is in practice currently in PHWR system:

i. D_2O leak detection and identification of leaking SG is possible during full-power operation of the PHWR,

ii. SG leak detection is possible during the initial stages of operation of PHWRs when ^{3}H activity level is very low in the primary coolant,

iii. the background buildup will not affect the process of identification of leaky SG,

iv. chemical quenching is non-existent, and colour quenching in steam condensate sample is negligible and hence quench correction to the measured value is not required and thus the design of the system is simple,

v. no flours, liquid scintillators, and other chemicals are required, and therefore the sample can be reused subsequently,

vi. no chemical waste is generated, and waste disposal problem is not associated with Cerenkov counting,

vii. identification of leaky SG during reactor operation without using scintillation chemicals makes the method environmentally benign and saves the economy.

The added advantage of the system is that it can as well be used in detecting D_2O leak in moderator heat exchangers of PHWRs with better sensitivity, as ^{19}O activity in the moderator water will be about one order higher than that of primary coolant water.

Cerenkov photon counter for leak detection will not respond to leak during reactor shut down due to the decay of the short-lived radioisotopes. Hence during the absence of the online system periodical, manual sampling and analysis for ^{3}H activity in secondary coolant using LSA have to be performed for leak detection.

Finally, it can be concluded that:

(i) through an in-depth study, an ideal system for SG/HX D_2O leak detection in PHWR type reactors was conceptualised.

(ii) through simulated and in situ experiments, the present study contributed to reactor technology by developing a rugged system for leakage detection in HX/SG, which is far superior compared to the existing systems.

(iii) a spin-off application of the system for estimation of thermal neutron flux by online Cerenkov counter is demonstrated.

This work has made a significant contribution to the frontier areas of nuclear science and technology. This study demonstrated that the presently developed system could be used for the quick detection of the leakage and also identify the leaking SG. Installation of such a system in NPPs which will help in the continuous online monitoring of D_2O leak during operation of a PHWR and minimise the radiological impact and waste generation.

6.0 Research publications in peer-reviewed journals, National and International Conferences/workshops related to the thesis work

i Dileep B.N. Ravi P.M., Managanvi S.S., Karunakara N.,2020, An advanced method for quick detection of heavy water leak in steam generators of pressurized heavy water Reactors, Nuclear Engineering and Design**,** 359, pp 1-10 https://doi.org/10.1016/j.nucengdes.2019.110447

ii Dileep B.N., Ravi P.M, Karunakara N., Managanvi S.S., Tripathi R. M. 2018. A new method for D_2o to H_2o leak detection and identification of leaky heat exchanger in PHWR by Cerenkov photon-counting technique, Nuclear Technology and Radiation Protection, Vol. 33, pp 325-333. http://doi.org/10.2298/NTRP180606012D.

iii Dileep B.N., Managanvi S.S., Rajeev M.S., Manjunath R.K., Naik S.B, Saradhi I.V., Ravi P.M., Karunakara K., Vinodkumar A, Determination of Oxygen-19 activity by Cerenkov photon-counting technique and its applications, 15th International Conference on Modern Trends in Activation Analysis, (MTAA-15), Bhabha Atomic Research Centre, Trombay, Mumbai, India, November 17-22, 2019.

iv Dileep B.N., Ravi P.M., Karunakara N., Rajeev M.S, Managanvi S S, Raichur P.G., Tripathi R M, Operating experience with online D_2O to H_2O leak monitoring systems in PHWRs and development of a new system to identify steam generator leak., Proceedings of International workshop CANSAS –2015 (CANDU Safety Association for Sustainability) & NRTHS –2015 (New Horizons in Nuclear Reactor Thermal Hydraulics and Safety) 8 –11 December 2015 Anushaktinagar, Mumbai, India

v Dileep B.N, Ravi P.M., Karunakara N., Rajeev M.S, Managanvi S S, Raichur P.G., Tripathi R M, A new method of detection of D_2O leak from heat exchanger of PHWR by Cerenkov photon counting technique., P M Ravi, N Karunakara, S J D Cruz, S S Managanvi, P G Raichur, R M Tripathi, proceedings of NSRP 20, Manglore University, Oct. 28-30, 2015.

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